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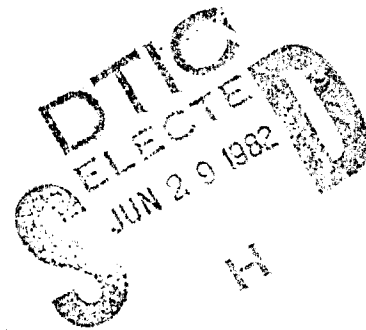
AFAMRL-TR-80-121



# **PROPOSED NEW VISION STANDARDS FOR THE 1980'S AND BEYOND: CONTRAST SENSITIVITY**

ARTHUR P. GINSBURG, MAJOR

SEPTEMBER 1981



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AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY  
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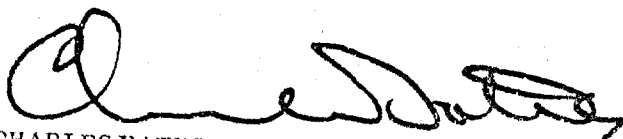
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FOR THE COMMANDER



CHARLES BATES, JR.  
Chief

Human Engineering Division  
Air Force Aerospace Medical Research Laboratory

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using the same method used to assess hearing. Just as hearing tests use sound intensity and temporal frequency to measure audiometric sensitivity, contrast sensitivity tests use contrast and spatial frequency to measure visual sensitivity. Because standard eye charts do not change contrast, they cannot measure vision sensitivity to any except the smallest size symbols. The relationship between contrast sensitivity and eye charts will be discussed using normal and abnormal vision. Although standard eye charts are useful to create an in-focus image in the back of the retina, contrast sensitivity techniques are needed to measure the next physiological state that determines the observer's response to that image. Data are presented that reveal individual differences in contrast sensitivity among normal observers that have definite implications for visual performance in operational environments. Since these differences in visual sensitivity can relate to detection and recognition ranges, these data can then be transformed into time to perform certain tasks and lead naturally towards visual standards being based on task performance under operational conditions. It is suggested that contrast sensitivity data be obtained in parallel with conventional vision tests to begin creating visual standards that relate to observer capability over the full range of operational environments.

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## SUMMARY

Present visual standards are generally based on the observer's ability to see small, high contrast black and white letters or symbols. Current research shows that such vision tests are not adequate to evaluate an individual's target detection and recognition capability over ranges of target size and contrast used in real situations. New vision tests are being developed that use the observer's report of the visibility of sine-wave gratings (that look like fuzzy bars) to assess visual capability with much more sensitivity than that of standard tests. The new tests, called contrast sensitivity, assess vision using the same method used to assess hearing. Just as hearing tests use sound intensity and temporal frequency to measure audiometric sensitivity, contrast sensitivity tests use contrast and spatial frequency to measure visual sensitivity. Because standard eye charts do not change contrast, they cannot measure vision sensitivity to any except the smallest size symbols. The relationship between contrast sensitivity and eye charts are discussed, using normal and abnormal vision. Although standard eye charts are useful to create an in-focus image in the back of the retina, contrast sensitivity techniques are needed to measure the next physiological stage that determines the observer's response to that image. Data are presented that reveal individual differences in contrast sensitivity among normal observers that have definite implications for visual performance in operational environments. Since these differences in visual sensitivity can relate to detection and recognition ranges, these data can then be transformed into time to perform certain tasks and lead naturally towards visual standards being based on task performance under operational conditions. It is suggested that contrast sensitivity data be obtained in parallel with conventional vision tests to begin creating visual standards that relate to observer capability over the full range of operational environments.

## **PREFACE**

**The author is a member of the Visual Display Systems Branch, Human Engineering Division of the Air Force Aerospace Medical Research Laboratory. Dr. Ginsburg is Director of the Aviation Vision Laboratory, under Project 2313V122, "Basic Visual Perceptual Processes for Displays."**

**Many of the data and much of the discussion in this report were presented at the Aerospace Medical Association Annual Scientific Meeting, Washington, DC, 14-17 May 1979 (p. 81-82) and at an invited presentation, "Emerging Techniques for Assessing Vision" at the National Research Council Committee on Vision Annual Meeting, National Academy of Sciences, Washington, DC, 15-17 April 1979. The information was also presented at the Advisory Group for Aerospace Research and Development (NATO/AGARD) Aerospace Medical Panel Specialists' Meeting at the Defence and Civil Institute of Environmental Medicine (DCIEM), Toronto, Canada, held from 15 to 19 September 1980. Although this paper will be published in the NATO/AGARD proceedings, it is being published as a technical report to make the information available to the wider research community.**

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## INTRODUCTION

The Air Force mission is to fly and fight. Although manned aircraft are projected to perform that mission well into the twenty-first century, today's high technology aircraft are outperforming the physical capabilities of the pilot and are creating increased workload that can seriously jeopardize the success of the mission. These facts demand the selection of pilots based on physical standards that complement his weapon systems and call to question currently accepted standards in many areas. One important physical standard relevant to virtually all Air Force missions is vision. Although one would question the importance of other complex tasks that the pilot is required to perform, vision is the only sensory system to be used to its fullest capacity. In spite of advanced electro-optical sensors, visual target acquisition remains the key to successful air-to-air combat. He who detects the enemy first has by far the greatest chance of survival and combat success. That dictum, echoed throughout aviation history, was recently reinforced by written comments obtained from 100 American air aces (Youngling et al., 1977). That study also found that visual target acquisition was rated as a more important critical combat skill than selecting and executing the best maneuver to gain a firing position. Further, superior vision can reduce workload. Increased detection range of targets means increased time for the pilot to perform combat related tasks that, in turn, can help reduce workload. Present and future missions will require pilots to have optimum visual capability; and visual standards must relate to that capability in terms of task performance.

Although no one would regard visual target acquisition as a simple function, current visual science allows that complex function to be divided into certain general subfunctions, for example, optical, physiological, and cognitive. Even these subfunctions are complex and the relationships between them are not fully understood. At least certain major aspects of the first two functions—optical and physiological—appear to be understandable and measurable today to the degree that meaningful standards for those functions can be considered. These two functions are discussed and are related to the possible creation of relevant visual standards based on observer capability that affects combat performance. This approach does not diminish the importance of cognitive factors in target acquisition. However, unless the optical quality of the eye creates an in-focus image at the retina and physiological mechanisms are sensitive to features of that image, then it is a moot point as to the motivation of the observer affecting performance. No amount of motivation can make up for the target not being physically seen. Complex visual performance is highly unlikely to be fully predictable in the real-world, except for certain limited tasks under special conditions. Until further gains are made in understanding complex visual function, our present goal should be to set standards optimizing the capability of visual functions that can be measured and are known to consistently affect performance.

The stress on general capability rather than specific performance is made because all too often visual standards, as well as other performance criteria, are required to be shown relevant to "real-world" performance before acceptance. On the surface, that requirement seems quite reasonable. The main problem with that approach is an endless list of "real-world" performance criteria based on sometimes quite different mission requirements. Relevant visual requirements for the combat pilot to detect a target under clear atmospheric conditions over a desert are quite different from that under low contrast conditions, such as those found in haze, fog, or smoke, that would exist in a European scenario. Present needs require visual standards relating to visual capability needed under all possible viewing conditions.

Present visual standards are primarily based on measures of visual acuity using the visibility of high contrast optotypes, such as Snellen letters. Unfortunately, visual acuity measures, based on high contrast targets, have not related well to visual performance, except under certain conditions of limiting resolution. By definition, acuity measures do not measure visual sensitivity over the range of object size and contrast relevant to many combat arenas; for example, the relatively high contrast environment of the daytime desert as compared with the low contrast European environment under twilight or dawn conditions. However, the limitations of acuity measures can be overcome using a more sensitive measure of visual capability: contrast sensitivity. This report presents data that show the limitations of acuity measures and the advantages of contrast sensitivity to help create vision standards that relate to the capability of performing certain military missions. For example, individual differences in contrast sensitivity have important implications for visual target acquisition, under a wide variety of conditions that are not measured by acuity tests. Finally, the implications of contrast sensitivity on target visibility, detection range, and workload are discussed.

## PRESENT VISUAL STANDARDS: VISUAL ACUITY

The first visual capability relevant to target acquisition is good optical quality—to have an in-focus image at the back of the retina. This capability of vision, by far the main criterion of all present visual standards, generally uses acuity measures to determine the optical quality of the retinal image. High contrast optotypes are typically used to measure visual acuity, usually in terms of resolution of gaps in Landolt rings, the orientation of letter E's, or the legibility of Snellen-type

alphanumeric characters. The basis for these tests is retinal sampling: intercone spacing of the retina limits visual acuity. These anatomical considerations lead to the notion that the retina, having an in-focus image, should be able to resolve approximately one minute of arc. Snellen-type characters are formed on a 5 x 5 element grid. Snellen line 6/6 (20/20 in feet) refers to the visibility of the size of targets that subtend 5 minutes of arc at a distance of 6 meters, each target having stroke widths that subtend 1 minute of arc. Good visual acuity is generally defined when an observer can perform the resolution or recognition task, using the fine detailed information from Snellen line 6/6 to 6/12. These types of acuity tests have certain distinct advantages. The patterns are simple to make because they have only one black and white level. They are simple to use, require no expertise on the part of the administrator, and with certain tests, no expertise required from the subject. They are quick and, in most cases, accurate to generally accepted standards. Further, the prints or slides are fairly inexpensive. Historically, acuity measures have been successful in helping refract the majority of eyes. These reasons suggest why Snellen-type acuity measures are widely accepted. However, with all these advantages, the distinct disadvantage to these techniques is their limit in being able to provide a measure of visual quality that relates to performance under most visual conditions. The acuity measure leads one to assume that the optimum optical quality of the retinal image insures optimum visual performance. However, by definition, an acuity measure can only give a single number relating to limited performance and can address little about visual performance up to that limit. Further disadvantages include the nonstandardization of conditions under which acuity measures are obtained throughout the world. Such factors as pupil size and level of illumination can affect visual acuity. Further, different kinds of optotypes require different amounts of resolution ability. These factors make acuity standards difficult to control and interpret. It is little wonder that the operational community balks at visual standards based on a single number that can so drastically affect a person's career. Recently, an attempt has been made to provide standard procedures for the clinical measurement and specification of visual acuity (National Academy of Sciences, in press). Even before other visual standards are considered, it seems, as a minimum, that the Armed Forces should standardize procedures for measuring and specifying visual acuity.

Clinical optotypes are primarily used to determine the optical quality of an individual which, in turn, is used to determine whether corrective lenses are required or not. The optotypes allow simple determination of whether an image is in or out of focus. An out-of-focus image causes the optometrist and ophthalmologist to attempt to correct the optical transfer function of the visual system. Since the optical transfer function of the visual system is a relatively simple linear function, then the correction of any one point of that transfer function will maximize the correction at all the other points. Thus, the types of measurements and specifications for optimizing the optical quality of the eye have been relatively relaxed. However, those same relaxed conditions can cause certain differences in final acuity measurements that could play havoc with studies that require consistent measures of visual acuity. Since acuity measures were designed to explicitly relate to optical quality, provide only a measure of limiting resolution under high contrast conditions, and are not standardized, it is little wonder that they do not relate well to visual performance under most conditions.

If on one hand there are many factors that affect visual acuity, this is balanced on the other hand by superior visual acuity, which evidently does not play an important factor in much of what we see. Although this may seem a bit paradoxical, our everyday perception provides many examples that much of our visual processing does not require information about the finest detail contained in objects. It is not uncommon for an optometrist or an ophthalmologist to find individuals that have not reported visual problems requiring 1 or 2 diopter correction. Although we certainly want the highest degree of visual quality for the pilot performing target acquisition, since initial detection is of prime importance for successful combat, we should also be aware that only one facet of visual perception, must be considered and other factors, such as sensitivity to larger objects having lower contrast, are more relevant for most viewing conditions.

Another important factor relevant to optical standards is whether or not optical aids can be used in the combat environment. Although no one would argue for dissimilar optical quality between an observer having 20/20 with or without corrective lenses (excluding of course large magnification changes), there are distinct disadvantages to wearing certain optical aids in the operational environment.\* Standard eyeglasses, for example, will become quite heavy under high G levels reached in air-to-air combat, they are also subjected to lint, haze, glare, slippage, and sweat, not to mention possible loss that can interfere with performance. Further, the frames of conventional glasses obscure targets at certain visual angles. Contact lenses are also prohibitive for similar kinds of reasons. An additional negative factor for contact lenses is the possible presence of dirt or other substances beneath the lens causing irritation. However, with an improved design of corrective lenses, it is possible that the problems associated with present glasses can be eliminated, or at least minimized.

\*Reported by Col T. Tredici to the Visual Standards Study Group, The School of Aerospace Medicine, Brooks, AFB, TX, 5-7 June 1980.

In summary, the optical quality is the first important step that one must deal with in optimizing visual target acquisition. Present visual standards should be dictated by the importance of initial target acquisition in combat. Thus, visual standards, in terms of optical quality, should be as high as possible, taking all other performance factors into consideration. Finally, standardized procedures for measuring and specifying visual acuity should be created. However, the creation of an in-focus optical image is but the first stage of vision and the next stage of visual processing, which deals with actual detection and other perceptual processes, must be considered. This next stage deals with sensitivity of the physiological retina-brain system that uses the optical image created at the back of the retina for subsequent target acquisition.

## PROPOSED VISUAL STANDARDS: CONTRAST SENSITIVITY

Over the past decade, an alternate method of testing vision has come into use in both the scientific and clinical communities. The method measures visual sensitivity, using targets called sine-wave gratings, that are specified in terms of two variables: spatial frequency and contrast. Schade, 1956 pioneered the use of spatial frequency and contrast as a means of assessing spatial vision. Since then, a number of significant contributions have been made by other researchers—Delange (1958), Lowry and DePalma (1961), Westheimer (1963), Kelly (1966), Robson (1966), Campbell and Green (1965)—that led to present methods for measuring contrast sensitivity. A sine-wave grating is a repeated sequence of light and dark bars that has a luminance profile, which varies sinusoidally about a mean luminance with distance. The width of one light and one dark bar of a grating is one cycle, or the period of the grating. The reciprocal of the period is the spatial frequency. Spatial frequency is expressed by the number of cycles of the grating that occur over a particular distance. The spatial frequency of an object can be expressed by cycles per object (cpo) dimension or, more commonly, by cycles per unit of visual angle. The number of cycles per object dimension is called normalized spatial frequency. It is determined by the size of the particular dimension of some part of the entire object and is independent of viewing distance. Cycles per unit of visual angle, more commonly called cycles per degree (cpd), is determined by the viewing distance. The luminance difference of the light and dark bars determines the contrast of the grating. The Michelson definition of contrast is most often used:

$$C = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

where  $L_{\max}$  and  $L_{\min}$  are the maximum and minimum luminances of the bars of the grating. Examples of sine-wave gratings having low, medium, and high spatial frequencies at low and high contrast are shown in Figure 1. The luminance distribution for each grating is shown below each grating patch.

If the contrast of a grating is increased from below its visibility to where the grating is just seen, then the grating is said to have reached threshold contrast. The reciprocal of the threshold contrast is called contrast sensitivity. Gratings of different spatial frequencies require different amounts of contrast to reach threshold for the observer. In a typical measurement session for contrast sensitivity, a subject adjusts the contrast of a sine-wave grating until the bars are just at the threshold of visibility. Measurements are repeated for a number of bar widths (spatial frequencies). The reciprocal of contrast threshold is plotted as a function of spatial frequency to create a contrast sensitivity function. A typical contrast sensitivity function is shown in Figure 2. The broad, inverted U-shaped curve describes the visual "window" that limits the range of the size of objects that can be seen under conditions of threshold contrast. The area above the curve is the region of low contrast where the visual system does not see objects because it is below threshold. Note that the visual system is most sensitive to sine-wave gratings at about 2 cpd, depending upon experimental conditions. Sensitivity decreases for spatial frequencies above and below peak sensitivity. As with auditory processing of temporal frequencies, only a limited range of spatial information can be passed by the visual system. The physiological limit is about 60 cpd, which depends upon viewing conditions. Techniques for obtaining suprathreshold contrast functions are also available, but that discussion is beyond the scope of this paper. The narrower curves shown within the contrast sensitivity function represent relatively narrow bandwidth mechanisms called "channels" that make up the overall contrast sensitivity function. These channels are suggested to play a major role in "filtering" relevant target information such as contrast, size, and basic form (Ginsburg, 1971, Ginsburg, 1977). Evidence for these channels and their relationship to visual perception is also beyond the scope of this paper. However, works reported by Ginsburg (1977) and Devalois and Devalois (1980) are suggested for the interested reader.

There are three general techniques currently used to measure contrast sensitivity to gratings: electronic generation for TV displays (Campbell and Green, 1965), film (Ginsburg, 1977), and photographic plates (Arden and Jacobsen, 1978). The TV displays provide the most accurate measurements; however, high levels of expertise in electronics, display technology, and/or computer hardware and software are required for best results. Gratings created on film can be imaged by standard projection techniques and their contrast can be controlled by polarizers (Ginsburg, 1977). The major requirement of this approach is being able to create high-quality sinusoidal gratings and other targets on film. Unfortunately, the precise

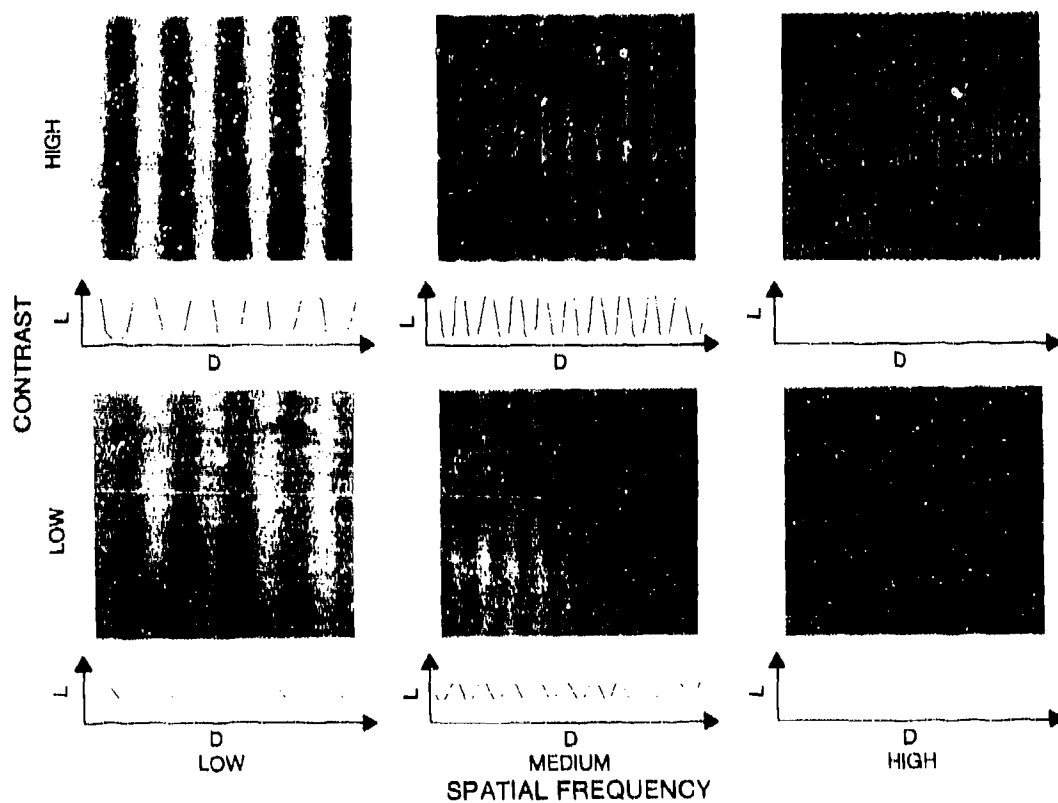
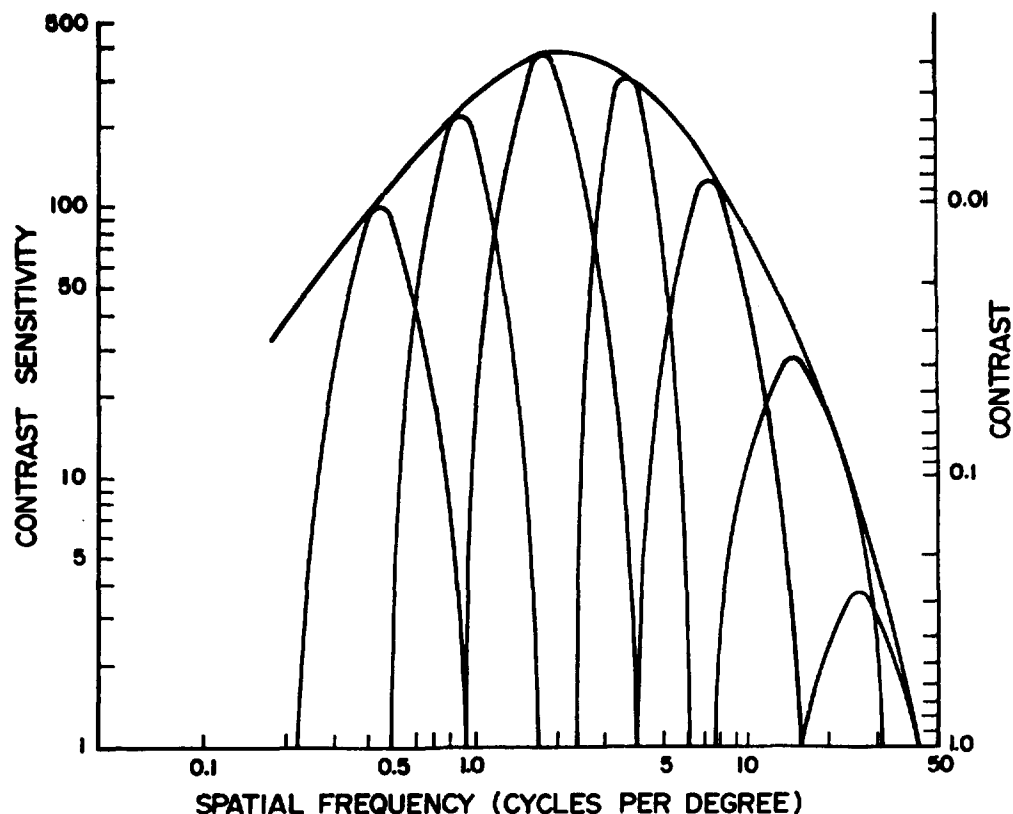


Figure 1. Examples of sine-wave gratings with low, medium and high spatial frequencies at low and high contrast. The luminance distribution for each grating is shown below each grating patch. Note that these gratings will have different visibilities depending upon viewing distance due to the visual filtering characteristics of the observer (Ginsburg, 1978b).

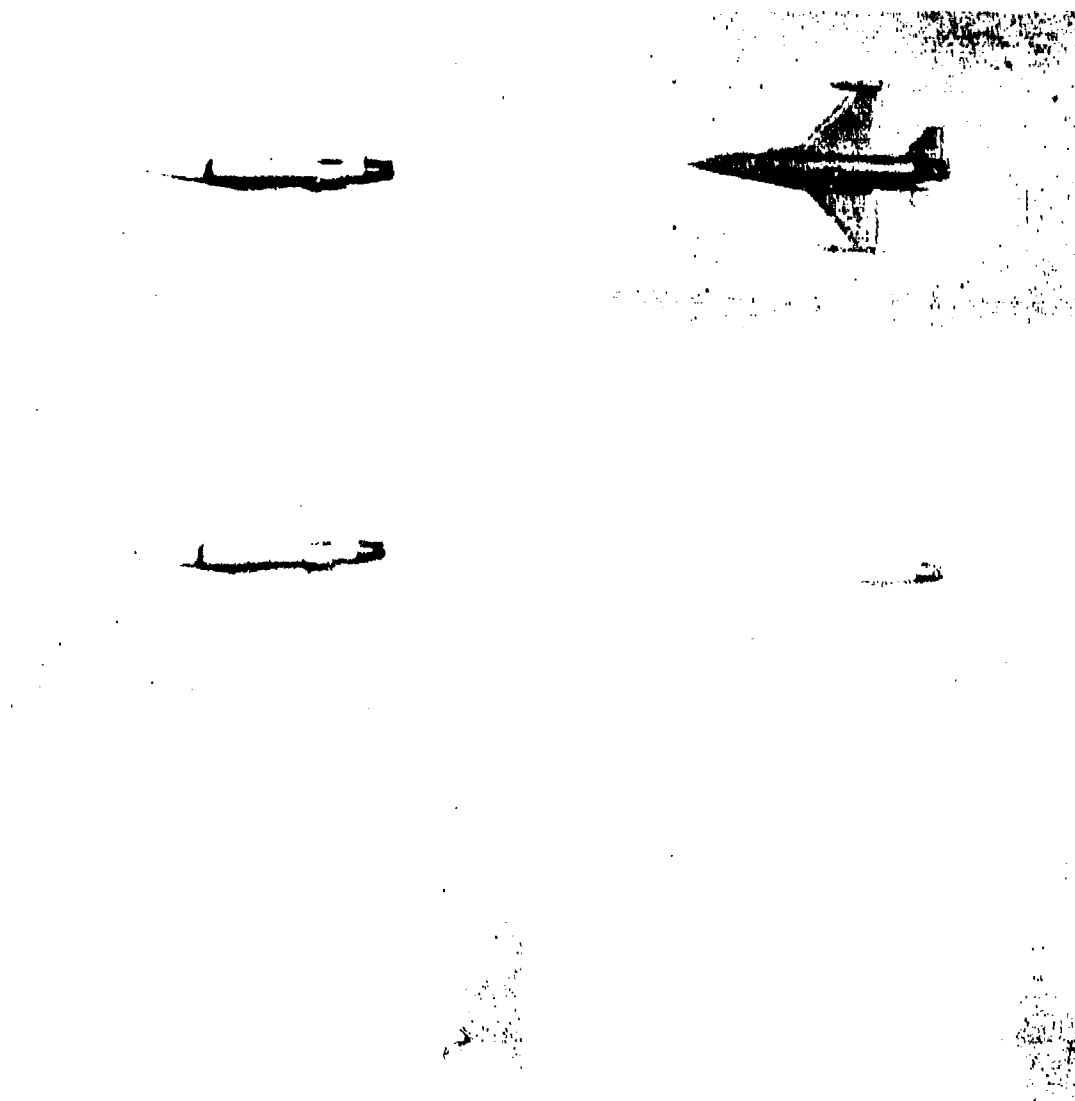


**Figure 2.** A typical threshold contrast sensitivity function is shown by the wide-band inverted U-shaped curve. Note that the visual system is most sensitive to threshold sine-wave gratings at about 2 cpd and is limited to passing spatial frequencies greater than about 60 cpd. The narrow-band curves represent channel filters based on biological data (Ginsburg, 1977; Ginsburg, 1978b (in press) ).

alignment of the optical components makes portability difficult without realignment. The third technique that uses photographic plates also has poor reproduction of gratings and large operator biases. Variations of these three techniques are being used and improved in the AFAMRL Aviation Vision Laboratory. In particular, research is on-going to create portable devices for measuring contrast sensitivity.

The importance of contrast in enabling one to see various spatial information in objects cannot be stressed too much. The loss of spatial information in objects with reduced contrast is demonstrated by the F-16 aircraft shown in Figure 3. Various details about the aircraft, such as the wing-tip missiles, are selectively lost as the contrast is reduced from 100% to about 6 percent. At the lowest levels of contrast, only a cigar-like shape remains. The series of pictures depicts the amount of visible detail that could be expected as a target flies into haze or clouds.

There are two main attributes of the contrast sensitivity test. First, since contrast is the depth of modulation of the grating about an average luminance, the average light level is kept constant, resulting in a constant state of retinal adaptation. This greatly reduces nonlinearities in measuring contrast sensitivity because the eye is at different stages of adaptation. It has been shown that the contrast threshold (Campbell and Robson, 1968), and more recently certain aspects of perceived suprathreshold contrast (Cannon, 1979; Ginsburg et al., 1980) are approximately linear. A high degree of linearity of processing spatial information allows the use of well-defined and easily implemented mathematical techniques to explain how objects are seen, whereas nonlinear processing greatly increases analytical complexity. Second, sinusoidal gratings are linear basis functions. This means, in mathematical terms, the single sine-wave grating is a very simple stimulus. It is one-dimensional and contains one frequency. Using Fourier techniques, any complex object can be broken down or built up from a combination of spatial frequencies having different amplitudes and orientations. This means that the spatial information in high contrast optotypes or any target can be determined from combinations of single gratings, as is described



**Figure 3.** A photographic series of an F-16 aircraft showing decreasing contrast. Note that the details such as the wing-tip missiles disappear before the larger features such as the wings and fuselage with decreasing contrast. Similar to the gratings shown in Figure 1, note that the features of these aircraft will have different visibilities upon viewing distance due to the visual filtering characteristics of the observer.

later. If certain assumptions are accepted that are beyond the scope of this report, then the contrast sensitivity function, which represents the general filtering characteristics of the visual system to sine-wave gratings, can be used to determine the visibility of any complex object (Ginsburg, 1977). Two-dimensional filter characteristics of the visual system can also be obtained from a combination of contrast sensitivity functions of one-dimensional gratings determined at a number of orientations; for example, at angles of 45, 90, and 135 degrees. This type of filter can also be used to predict visibility of objects (Ginsburg, 1973). This approach provides a powerful, unifying basis for research into complex target acquisition using simple filter functions based on visual data. Moreover, this approach, since it uses the same language used by engineers, allows a natural step to be taken to determine relevant spatial information presented to observers for display design and image quality (Ginsburg, 1980). Finally, the contrast sensitivity approach with which to probe vision is becoming a more widespread tool among scientists. Many factors which affect the shape of the contrast sensitivity function have been studied. For example, the effects of luminance, focus, field size, peripheral view, chromaticity, and others have been measured (Farrell and Booth, 1975). Thus, much is known about the general behavior of contrast sensitivity functions under operationally relevant conditions. Basing visual metrics on these techniques will allow quick integration of knowledge in current science into applied areas.

Although contrast sensitivity appears to provide a more complete measurement of spatial vision than acuity measures, unless the filter characteristics can be used to relate visual capability to visual performance such as target acquisition, then its power will be limited. What is needed is a relationship between contrast sensitivity and the visibility of complex objects. That relationship is presented next.

A general relationship between contrast sensitivity and the visibility of Snellen letters has been determined (Ginsburg, 1977). It is pointed out that Snellen letters represent a set of overlearned complex two-dimensional targets. Two pieces of information were needed to establish that relationship: the minimum number of spatial frequencies and the minimum contrast required for the recognition of Snellen letters. The number of cycles necessary for the recognition of Snellen letters was determined by Fourier synthesis of a letter L and a letter E, in steps of 0.5 cycles per object (cpo) as shown in Figure 4. These letters were chosen because the E is more difficult to resolve than the letter L. First note that the energy contained in the frequencies below 1 cpo allows detection to occur but not recognition. For recognition to occur, 2.5 cycles are required for E, but only 1.5 cycles are required for the L. It should be clear that this is the reason for the L being recognized

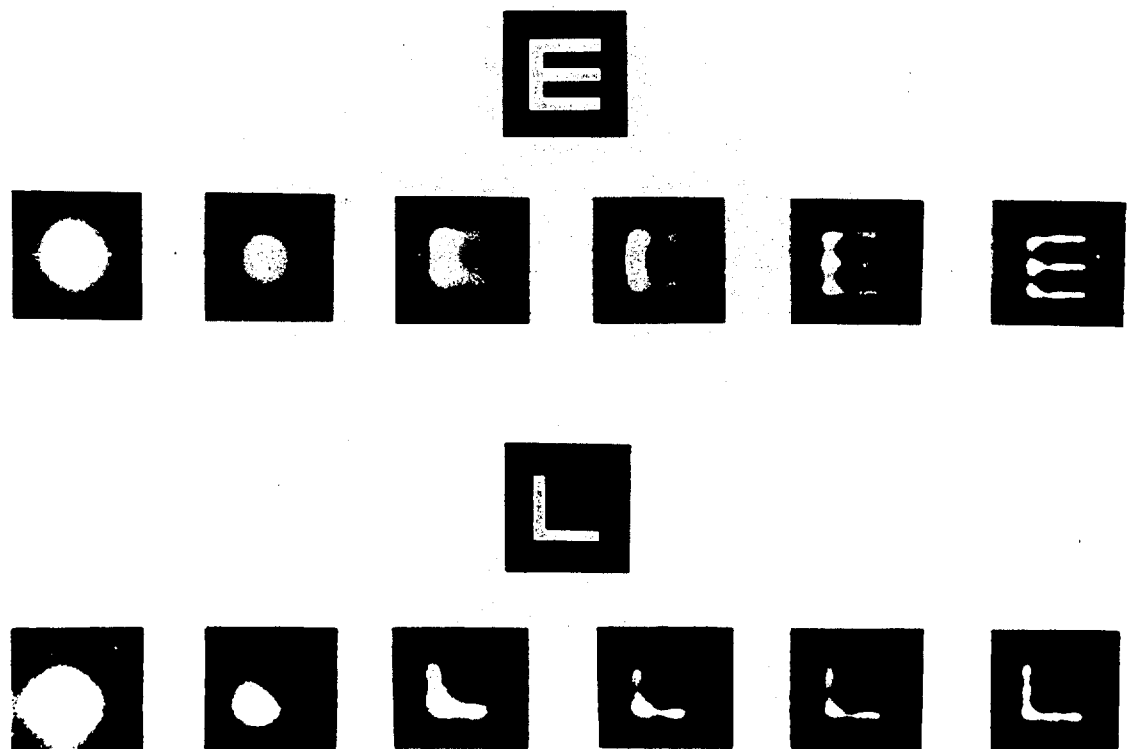


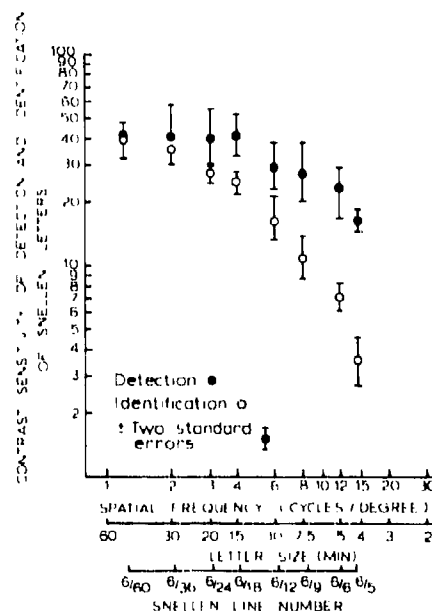
Figure 4. Fourier synthesis of Snellen letters E and L in increments of 0.5 cpl. The synthesized filtered images of the E and L are shown below their respective letters: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 cpl (Ginsburg, 1977).

at a greater distance or smaller angular subtense than the E. These results suggest that a bandwidth (the relevant number of spatial frequencies for a particular task) of about 1.5 to 2.5 cpo is required for the recognition of Snellen letters (Ginsburg, 1977; Ginsburg, 1978). This result would not be intuitively obvious from using resolution criteria of visual acuity. For example, previous attempts to relate Snellen acuity to contrast sensitivity used the visibility of stroke width as the criterion for recognition. For Snellen letters, the stroke width is 1 minute of arc, which equals 30 cpd. That analysis suggests the recognition of the Snellen letters should occur when the letter stroke is visible, i.e., when contrast is great enough to allow the frequency of 30 cpd to reach visual threshold. However, it is well known that L is more visible than an E. Therefore, this very common approach used in much previous research can lead to wrong conclusions about spatial information in objects used for target acquisition. These results show that it is the two-dimensional distribution of the target features that determines their visibility.

The next step related the relevant spatial frequencies required for recognition to the contrast sensitivity of the visual system to those spatial frequencies. That required knowledge about the minimum level of contrast (contrast threshold) for the detection and recognition of letters subtended at the different visual angles that correspond to the different size letters for each Snellen line. Those results, using typical Snellen letters, are shown in Figure 5. For large Snellen letters, note that detection and recognition thresholds are very similar. An everyday experience of this is seeing a person or an object appearing suddenly out of fog at close range or a pilot flying through smoke, haze, etc. However, for small Snellen letters, there is a large difference between the detection and recognition. The smallest letters used, Snellen line 6/5, requires a factor of about 4 to 5 in contrast from detection to recognition. We have all experienced this effect, even in conditions of good visibility, when we detect an object easily but find we must get very much closer for correct recognition. A more relevant example is a pilot who detects a target at 20 miles but travels an additional 10 miles before correct recognition occurs.

Another way to look at the finding that certain large objects can be recognized as soon as they are detected under low contrast conditions is in terms of the bandwidth of cycles per object necessary for this task. Large Snellen letters whose overall size is 60 minutes (') of arc have a fundamental frequency of one cycle per degree. The 1.5 to 2.5 cycles per letter necessary for recognition occur at spatial frequencies from about 1.5 to 2.5 cpd. The typical contrast sensitivity function, Figure 2, shows that these spatial frequencies are all at or near peak visual sensitivity. When the relevant frequencies are all at or near peak visual sensitivity. When the relevant frequencies required for detection reach threshold near peak sensitivity, the spatial frequency components in the bandwidth required for recognition, having spatial frequencies up to about

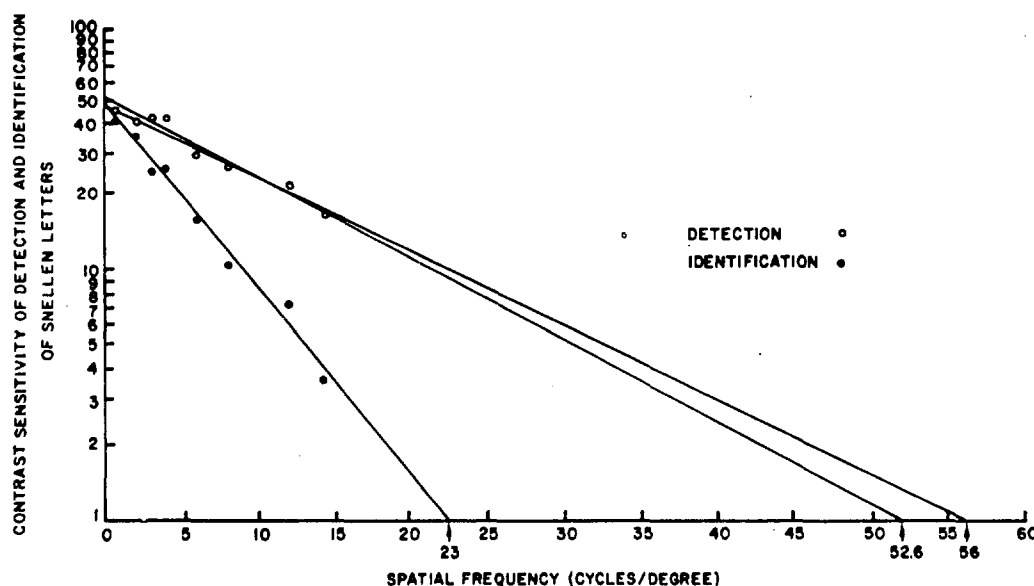
**Figure 5.** Contrast sensitivity for the detection and identification of at least 50% of the Snellen letters on each line of a typical Snellen chart. The contrast sensitivity is the reciprocal of the threshold contrast needed for detection and identification of the letters. The spatial frequency ( $f$ ) is the fundamental spatial frequency or 1 cpl for the letters on each Snellen line ( $f = 60/\text{size of letter}$ ). The Snellen line number is given in meters. Snellen lines 6/60 and 6/6 are similar to 20/200 and 20/20. These contrast sensitivity values will change somewhat due to field size and average luminance and should not be taken as absolutes (Ginsburg 1977).



2.5 cpd, are also reaching threshold at about the same time. Thus, the spatial frequencies used for detection and recognition of these targets reach threshold almost simultaneously. However, note that a letter on Snellen line 6/6 has a size of 5 minutes, corresponding to a fundamental frequency of 12 cpd. The 1.5 to 2.5 cycles for this letter corresponds to 18 to 30 cpd. Thus detecting at or below 12 cpd now requires 4 to 5 times more contrast to get the spatial frequencies from 18 to 30 cpd above threshold so recognition can occur. Certain targets can be created such that detection and recognition can occur simultaneously at any distance (Ginsburg, 1977).

The bandwidth required for recognition of Snellen letters determined from the filtered letters of about 1.5 to 2.5 cycles per letter also can be determined directly from these data. By replotted Figure 5 in terms of log contrast sensitivity versus linear spatial frequency, shown in Figure 6, note that the regression lines provide the bandwidth used for detection and recognition. Depending upon the particular spatial frequency at which the peak of the contrast sensitivity occurs, the bandwidth is about 2.4 cycles per letter. This result confirms the earlier filtering results of these letters. Further, these methods provide a general paradigm with which to determine the relevant bandwidth of spatial frequency information in any target from detection to classification, recognition, identification, and discrimination. Note that the regression line that excludes the data points before peak sensitivity crosses the spatial frequency axis at 56 cpd, very near the physiological limit of 60 cpd. This technique can be used to provide a very sensitive measure of an individual's limit of visual acuity. Thus the basic data required to make predictions of Snellen acuity from contrast sensitivity measurements have been obtained: the amount of contrast and the relevant spatial frequencies of these objects necessary for recognition. Validation studies of this approach have been conducted. Highly unusual contrast sensitivity functions from patients having amblyopia (a dimness of vision that cannot be corrected by optical means) and multiple sclerosis (a neurological disorder that affects vision) were determined and used to test the predictive power of this approach. In sum, based upon the contrast sensitivity of individuals having those visual disorders, the Snellen acuity of 17 out of 22 eyes could be predicted within one Snellen line, the other 5 eyes predictable within two Snellen lines (Ginsburg, 1977; Ginsburg, Oct 1978). Thus these data suggest that the contrast sensitivity function can be viewed as a filter that can predict the visibility of complex targets.

One robust feature of this research is that the contrast sensitivity function can predict poor visibility of certain patients when Snellen acuity predicted normal vision. For example, the contrast sensitivity function shown in Figure 7 is from a patient with multiple sclerosis (MS) who complained about the quality of vision in one eye compared to the other. This pa-

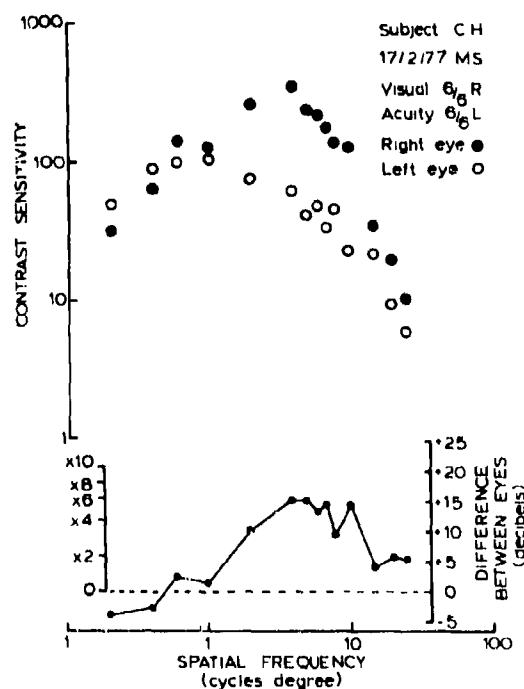


**Figure 6.** Contrast sensitivity for the detection and identification of Snellen letters shown in Figure 5 replotted using log-linear axis. Regression lines drawn through the data points are extrapolated to the x-axis. The two different lines through the detection data exclude and include the first three data points at peak sensitivity respectively. The similarity of these detection results suggest that the data obtained after peak sensitivity will give reasonable results relatively independent of changes in peak sensitivity. The spatial frequency bandwidth required to go from detecting to identifying these letters is  $56/23 = 2.4$  cycles per letter width (Ginsburg, 1977).

tient was measured, using Snellen acuity, as having normal of 6/6 vision. However, the ratio of contrast sensitivity between the two eyes is about a factor of 4 over almost a factor of 10 range of spatial frequency. Why is Snellen acuity not measuring this obvious difference in sensitivity between the eyes? The answer comes from the previous discussions. It was shown that 6/6 vision needs a certain amount of contrast sensitivity from about 18 to 30 cpd. A closer examination of the contrast sensitivity function of this patient with MS shows sufficient contrast in both eyes over the range of spatial frequencies required for 6/6 acuity. This result shows that Snellen acuity is not measuring sensitivity to obviously important ranges of object size less than about 18 cpd because the Snellen letters have only one level of high contrast. Similar results showing the inadequacy of Snellen acuity were also found by Ginsburg (1977) and Ginsburg (1978). The message is clear. Snellen acuity is not measuring the degree of visibility of objects over a large range of sizes because it does not take into account visual sensitivity to contrast. The auditory equivalent to Snellen acuity is to use only one high level of loudness for all sound frequencies tested. The sensitivity to sound would be measured from only 12 khz to 20 khz, excluding very important sensitivity to sound frequencies from 50 khz to 12 khz. Limited measurement in vision should not be accepted any more than limited measurement is accepted in audition.

The reason that Snellen acuity and other types of resolution criteria have been reasonably successful in both the measurement and correction of spatial vision is understandable. As previously pointed out, Snellen acuity can be used successfully for refraction because the vast majority of visual problems are optical in origin. Since the transfer function of an optical system is, in general, well behaved, the measurement of one point can be used to determine the performance over a large range of other points. Using a lens to correct one point for Snellen acuity will, in general, increase the visibility of objects at all the other points. However, if there are physiological differences in sensitivity or a visual deficiency is neurological and/or visual conditions are such that the measured resolution limit is not being used and an observer is forced to use lower spatial frequencies and contrast, then visual quality cannot be determined by resolution measures alone. That is why certain patients complain about poor visual quality that is tested normal using Snellen acuity.

**Figure 7.** The contrast sensitivity functions of each eye from a patient with multiple sclerosis. This patient complained about the poor quality in the left eye even after it was tested to have normal Snellen acuity. The complaint was real as evidenced by the difference in contrast sensitivity between the eyes shown in the upper and lower (the visuogram) curves. This dramatically shows the poor ability of Snellen-type measures to determine the general quality of spatial vision. (Ginsburg, 1977).



## CONTRAST SENSITIVITY AND TARGET ACQUISITION

It has been shown that Snellen acuity does not measure visual sensitivity below about 18 cpd. This means that the relative visual sensitivity between pilots or other observers to reduced contrast targets whose size is larger than about 3.3' is not known. Normal Snellen acuity means that targets whose size is larger than 3.3' can be seen at high levels of contrast. However, any conditions that reduce target contrast to the pilot; for example, low target-to-background contrast, atmospheric and windscreen haze, smoke, clouds, aerosols, or certain chemicals, force vision to use lower spatial frequencies to which visual sensitivity is not being measured using current vision tests and thus is not known. A similar situation exists for display operators, photointerpreters, x-ray diagnosticians and any other observers when their visual tasks are performed under similar reduced contrast conditions.

Unfortunately, there are no definitive population studies of contrast sensitivity to date that can be used to determine the degree of differences in sensitivity that could be used to relate to the ability to visually acquire targets. One conservative set of data is available however, that can provide at least a first approximation to individual differences in a normal population. One study determined population estimates of average contrast sensitivity measurements (Farrell and Booth, 1975). The average contrast sensitivity function was a "very approximate fit to the better visual performance data" of eight different studies. Visual performance was measured in terms of threshold contrast modulation for disks and sine- and square-wave gratings. These data are shown in Figure 8. Here threshold contrast is plotted rather than threshold contrast sensitivity. The solid line is the average subject data. The dashed lines are limits for 90 percent of the population. The maximum and minimum values of threshold contrast from these data for 1, 5, 15, and 30 cpd are shown. The average difference of 2.36 in sensitivity exists for 90 percent of the population. Note that the differences in sensitivity change with spatial frequency. The greater the sensitivity, the smaller the target that can be seen at the same distance. The expected visual performance for low contrast targets of two observers, one having the lower sensitivity curve and the other having the higher sensitivity curve can, in general, be understood from these data. The more sensitive person will see, on average and if all

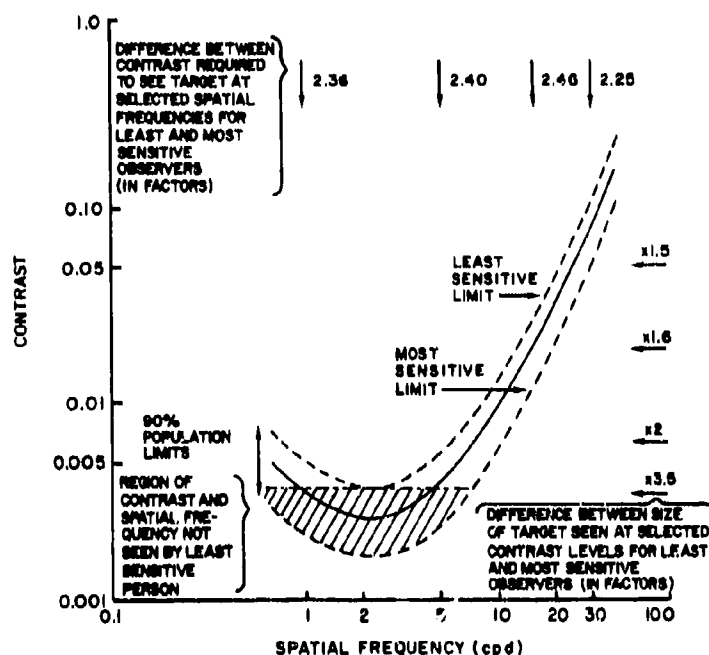


Figure 8. Average threshold contrast to detect disks and sine- and square-wave gratings is shown by the solid line. The dashed lines are 90 percent population limits. See text for explanation (after Farrell and Booth, 1975).

other factors are held constant, the same size target 2.15 times further, or a target 2.15 times smaller at the same distance, than that of a less sensitive person. In particular, the more sensitive person can see a low contrast target at 7 cpd when a less sensitive person can see the same target at 2 cpd and cannot see similar contrast targets smaller than 2 cpd. In terms of target size, this means that a less sensitive person is just seeing a 30' size target when a more sensitive person is seeing an 8.6' target, 3.5 times smaller. The more sensitive person will see a 30' size target 3.5 times farther (or more easily, i.e. higher signal-to noise ratio in case of photointerpreters and display observers) than that of a less sensitive person. Indeed, the cross-hatched region shows certain levels of low contrast where the more sensitive person can see targets ranging in size from about 0.5 to 8 cpd or 2° to 7.5' when the less sensitive person cannot see targets of any size. These are the maximum differences that can be postulated from this study. The difference in sensitivity decreases for higher spatial frequencies or smaller target sizes. For examples, at 20 cpd or for a 3' size target, the increased sensitivity results in increased target size by a factor of 1.5. These increased distances of target acquisition could provide increased time for a pilot to use to optimize tactics and other combat related tasks, and thus can help reduce workload.

The preceding analysis suggests that there are important differences between visual observers that have different contrast sensitivities that have direct implications for the selection of pilots and others whose visual ability is important for task performance. It would seem that observers having increased contrast sensitivity will be capable of acquiring targets further away than less sensitive observers under certain circumstances. Furthermore, this analysis may provide a basis for understanding and quantifying the quite common anecdotal comments about superior visual performance of "air aces." The conservative difference of a factor of 2.5 in contrast sensitivity between a high sensitive individual and low sensitive individual has definite implications for target visibility. For example, only a factor of 1.5 to 2.0 increase in contrast is needed to go from chance detection to almost certain detection. This means that, when all other factors are held constant, the high sensitive observer is certain that a target is detected when the low sensitive observer may still be guessing. Further, there is about a factor of 2.5 between the contrast of the lightest and darkest features of the F-16 aircraft in Fig 3c and that of Fig 3e. Therefore, there will be conditions where a high sensitive observer may be able to identify the aircraft and know in

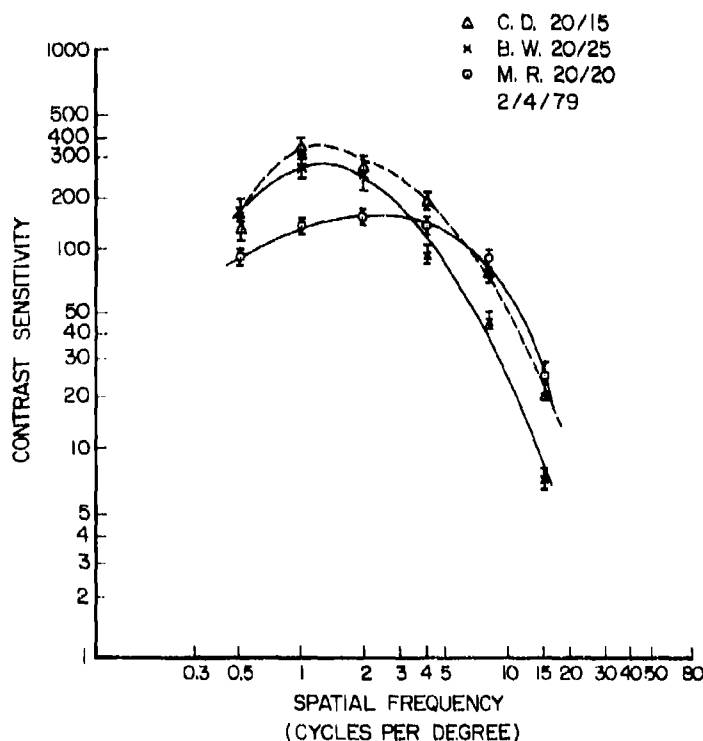
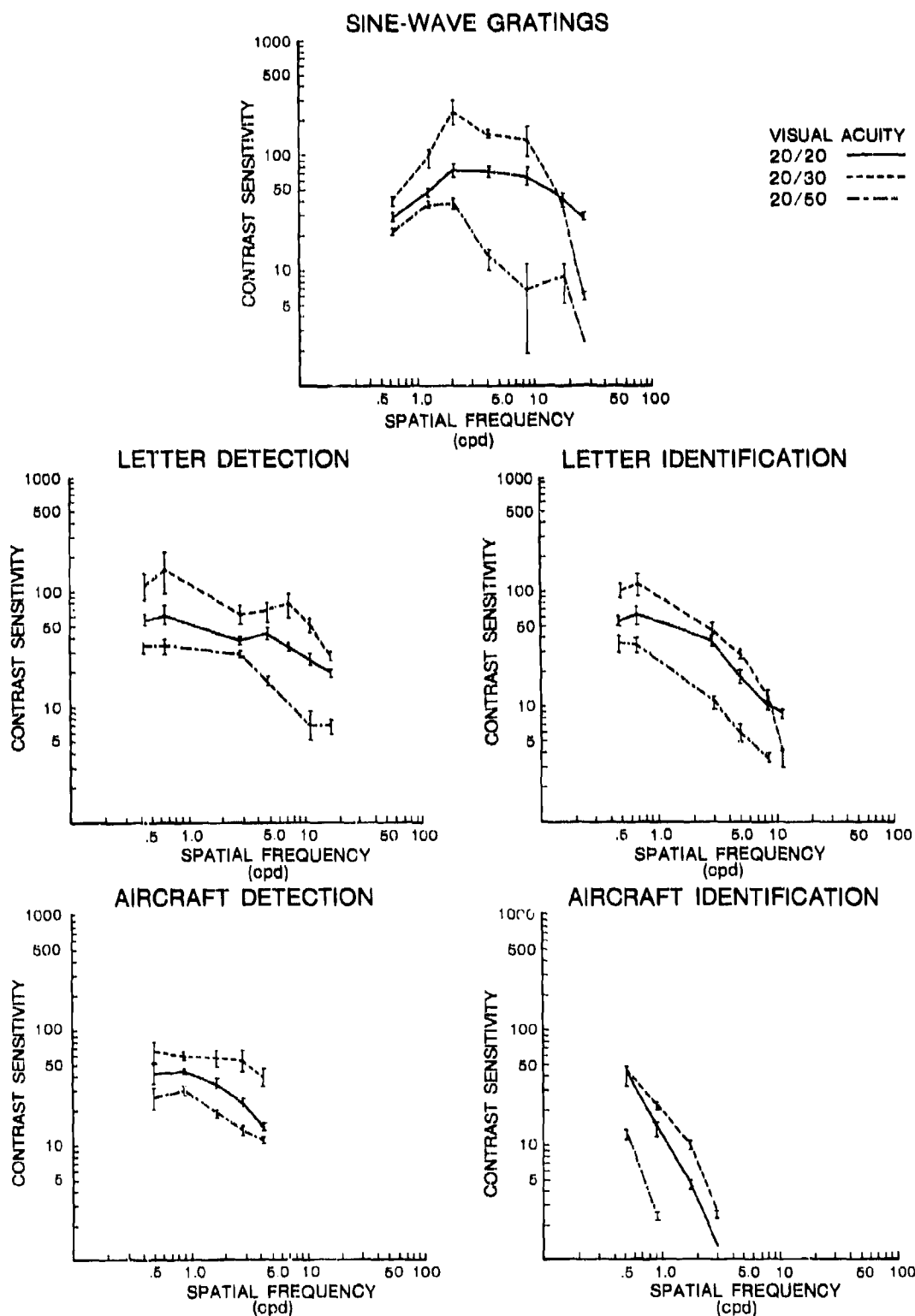


Figure 9. The contrast sensitivity functions of three pilots. Although pilots CD and MR have normal Snellen acuity (shown to the right of their initials), significant differences in their contrast sensitivity below about 7 cpd are found. These differences may have important consequences for task performance, as discussed in the text (from Ginsburg, 1978b).

The next stage in this research has been to investigate the degree of variability in contrast sensitivity among Air Force populations. Only small population studies have been obtained to date. However, interesting individual differences have been revealed, e.g., the contrast sensitivity over different ranges of spatial frequency. Pilot M. R. would be more sensitive to low contrast objects which have relevant spatial frequencies higher than 6 cpd whereas his sensitivity is greatly reduced for lower spatial frequencies. Similar results were found in another contrast sensitivity study that also determined the ability of subjects to detect and identify targets (Ginsburg and Evans, in press). The data shown in Figure 10 were obtained using two subjects having 20/50 and 20/30 Snellen acuity without their glasses and one subject having normal Snellen acuity, 20/20. The differences in Snellen acuity between these subjects agree with the differences in contrast sensitivity for spatial frequencies smaller than 16 cpd: decreased Snellen acuity corresponds to decreased contrast sensitivity. However, note the large differences in contrast sensitivity between the subjects having 20/20 and 20/30 acuity from 6 to 16 cpd that are not predicted from the Snellen acuity. The question whether or not these differences in contrast sensitivity are functional is answered by the subjects' ability to detect and identify Snellen letters and aircraft silhouettes under low contrast conditions. In almost every case, the subject having 20/30 was significantly more sensitive than the subject having 20/20. The one notable exception is the letter identification task for the smallest letters where fundamental frequency was 12 cpd. The subject having 20/20 was more sensitive than the subject having 20/30. However, from the previous analysis, a letter with fundamental frequency of 12 cpd means that the relevant spatial frequencies for letter identification will be about 18-30 cpd. It would be expected that increased ability to identify Snellen letters would require increased contrast sensitivity of sine-wave gratings for 18-30 cpd. That result is quite evident from the data. The reversed performance for letter identification between those two subjects at the higher spatial frequencies is predicted from their contrast sensitivity functions and from their Snellen acuity. Therefore, contrast sensitivity to sine-wave gratings appears to be able to relate to certain aspects of target acquisition over the full range of target size.

These data have shown that significant differences can and do exist between individual contrast sensitivity that determine the amount of contrast necessary for an individual to detect and identify targets having sizes vary over a large range. Although these data relate to limited scenarios in which targets are slowly moving or stationary and/or under conditions of ocular pursuit where the target remains somewhat localized on the retina, this approach may also be applicable to more dynamic conditions of target acquisition, such as rotation and zoom, where targets rapidly change position, direction, orientation, and size. However, current visual science suggests that static and dynamic targets are processed by somewhat independent visual mechanisms (e.g. Breitmeyer and Ganz, 1976). This means that tests of static visual acuity will not necessarily relate to dynamic visual acuity and that those kinds of functions will require separate tests. This is precisely what Ludvig (1960) found in early studies of dynamic visual acuity. Those studies showed quite large individual differences in dynamic visual tasks that required the detection of Landolt targets presented at different velocities. Unfortunately, there has been little follow-on work in that area. However, we have begun using the preceding contrast sensitivity approach to determine individual ability to detect and identify simple and complex targets under dynamic conditions. Our pilot studies show significant individual differences within and between static and dynamic target conditions. This approach will be extended to other operationally relevant viewing conditions such as low luminance (night-time conditions) and peripheral viewing. The main point to be emphasized is that there cannot be any unitary measure of visual capability that will be relevant to all possible viewing conditions. Needed are tests of visual capability that relate to the different target and viewing conditions that will be encountered in the operational environment. The approach presented here, using static targets, represent a first step in that direction. More work will be needed to determine the relative importance of each of these kinds of tests for visual target acquisition.

The dichotomy between the physiological and cognitive aspects of target acquisition created in the introduction of this paper is not that clean cut. What part of individual differences used in detecting and identifying the targets shown in Figure 10 are due to physiological or cognitive factors, such as threshold criterion or the particular selection of relevant target features, needs to be determined. Pilot experiments in our laboratory using non-criterion free paradigms, such as method of adjustment and a review of contrast sensitivity data using sine-wave gratings in criterion free signal-detection paradigms, reveal that about a factor of 1.5 to 2 in contrast is needed to go from chance detection to almost certain detection (e.g. Furchner et al., 1977). It would seem, therefore, that factors other than criterion are required to explain differences in individual contrast sensitivity when they differ by more than a factor of 2. Although the relative importance of such factors as physiological sensitivity and criterion could be determined experimentally, the finding that the individual's contrast sensitivity to gratings relates to his ability to detect and identify complex targets suggests that these differences are functionally important regardless of the degree to which physiological and cognitive components each adds to the result.



**Figure 10. Contrast sensitivity to sine-wave gratings, and detecting and identifying letter and aircraft silhouettes for two subjects having 20/50 and 20/30 Snellen acuity without their glasses and one subject having normal (unaided) Snellen acuity, 20/20. See text for explanation (from Ginsburg and Evans (in preparation) ).**

These results have concentrated on the implications of individual visual capability at near threshold levels of contrast. Although those regions of contrast are important in many operational environments, a large amount of viewing also uses suprathreshold levels of contrast. There is evidence that individual differences exist in the suprathreshold contrast perception (Georgeson and Sullivan, 1975; Cannon, unpublished\*). The degree of importance that these differences will play in the various aspects of target acquisition is not clear; however, it would seem that once target information is above threshold that sufficient contrast exists for any perceptual task. Although one individual may see that information at a higher contrast level than another individual, relatively small differences in visibility may not be significantly beneficial. Indeed, in certain cases it may be harmful. Consider, for example, where two individuals are viewing a video display on which relatively high contrast, high frequency noise and/or scan lines are visible. Since it is well known that high spatial frequencies mask low spatial frequencies (Stromeyer and Jules, 1972), it would follow that the more visible the high frequency noise, the more masking or the less visible would be certain lower frequency targets. On the other hand, increased target contrast does mean increased dynamic range which could in other cases provide increased signal-to-noise conditions that relate to image quality. For example, increased suprathreshold contrast perception may provide an increase in the number of perceived grey-scale values which could increase the contrast discrimination of different target information. In any case, how individual differences in perceived suprathreshold contrast relate to visual target acquisition awaits further experimentation.

These differences in individual visual capability also have implications for pilot workload. Today's high technology aircraft coupled with more complex combat environments create high workload conditions. Many decisions critical to combat success demand complex tasks to be correctly performed in short time spans of several seconds. Any increase in time to perform those tasks is important. Since distance equals rate times time ( $d = rt$ ), increased target acquisition range and/or certainty of target acquisition will offer the pilot more time to perform other critical combat-related tasks. Therefore, optimizing visual capability may in many instances reduce operator workload. Here too, further experimentation is needed to determine the relative importance of superior vision in complex environments. However, the data so far indicate that at least under some conditions, individual differences in contrast sensitivity could play a major role in certain cases of early target acquisition.

In summary, for vision-limited tasks, such as target acquisition in a high performance aircraft, the pilot should have maximum optical and physiological visual capability. Although more data are needed to determine population variances in contrast sensitivity and how those variances relate to complex target acquisition, given that all other relevant factors are equal, and whenever possible, it is suggested that observers with the highest contrast sensitivity be placed in the most vision-intensive tasks. The placement of high sensitive individuals in positions requiring high visual capability may not guarantee their success under all conditions. However, it will at least optimize the probability of success under many conditions that require visual target acquisition.

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\*Mark W. Cannon, Air Force Aerospace Medical Research Laboratory, unpublished data

## CONCLUSIONS

This brief report presents data that show the limitations of present visual standards based on acuity measurements in being able to measure normal as well as abnormal visual function in a manner that relates to visual performance over a wide variety of operational environments that affect contrast. A more powerful and parsimonious measure of visual capability—contrast sensitivity—is presented. Important differences between individual contrast sensitivity functions are shown to relate to one's ability to detect and identify letters and aircraft targets over a large range of target size and contrast under static viewing conditions. Present research is extending those results into dynamic viewing conditions. The collection of large population data of contrast sensitivity that is needed to determine the extent of normal variance has begun. Simulator studies that will lead to field trials that relate individual contrast sensitivity to various aspects of target acquisition are scheduled. Although we are still a long way from being able to establish new vision standards based on these emerging techniques, it is recommended that standardized testing equipment and procedures be developed to begin the collection of contrast sensitivity data in parallel with conventional vision tests. At a minimum, contrast sensitivity can be used to screen very high and very low sensitive individuals for further testing and/or observations. In addition to building up a data base, early exposure of the medical and operational communities to contrast sensitivity tests will sensitize individuals to limitations of acuity measures and encourage quicker acceptance of new visual standards based upon these techniques as they may develop. Especially important to the operational community is that the contrast sensitivity results will continue to be related to task performance that in turn will encourage the medical and operational community to work more closely together in establishing and maintaining relevant visual standards. We hope that it will not be too long before those contrast sensitivity techniques can be used to create standards that have the potential to help optimize the capability of that most important component of visual target acquisition: the human observer.

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